Data Production on Past and Future NASA Missions

Lee E. Z. Jasper
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-3678
lee.jasper@jpl.nasa.gov

Peter Xaypraseuth
Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-393-1601
peter.xaypraseuth@jpl.nasa.gov

Abstract—**Data return is a metric that is commonly publicized for all space science missions. In the early days of the Space Program, this figure was small, and could be described in bits or maybe even megabits. But now, missions are capable of returning data volumes two or three orders of magnitude larger. For example, Voyager 1 and 2 combined produced a little over 5 Terabits of data in 39 years of operation. In contrast, the Cassini mission, launched two decades after Voyager, produced about one and a half times those data volumes in half the time. NISAR, an Earth Science Mission currently in implementation, plans to produce over 28 Petabits of raw data in just 3 years. This means that NISAR will produce about as many data in 30 days as the combined data production of nearly all planetary missions to date. These increases in capability are a result of technology enhancements in two main areas: telecommunications architecture (both space and ground segments) and data storage technology. This paper describes the progression of these two technologies over the course of more than three decades of space missions and provides additional insight into the design of the end-to-end NISAR Data System Architecture. Trends in the data are briefly explored and compared to Moore's Law which provides only a qualitative model for memory growth but not for data production. In summary, early missions are found to be driven by unrefined processes while later missions, having utilized earlier lessons learned, focus more on improvements to flight and ground capabilities. Data return seems to fall into three categories. First, deep space missions are driven by the large distances that limit data return to the Earth. Next, the orbiter infrastructure around Mars helps these missions generate more data than other deep space spacecraft. Finally, near-Earth missions have the greatest capabilities for the studied metrics due to their close proximity to Earth and the ground network availability.**

TABLE OF CONTENTS

978-1-5090-1613-6/17/$31.00 ©2017 IEEE

1. INTRODUCTION

The key product for all of NASA's unmanned missions is data. Data are what drives the science, and are what every mission must create, store, and eventually return to Earth. The process by which the data is handled is complex and has gone through a number of changes throughout the last four decades. However, the main components have remained unchanged. Telecommunications are required due to the separation between the instruments producing the data and users of the data on Earth. Because the instruments often produce data out of sight of Earth ground stations or produce more than can be downlinked in real-time, on-board storage is required.

While the fundamental need for telecommunications and on-board data storage remains, technology has changed, increasing the capabilities of missions. Telecommunications continues to be one of the primary bottle necks for data delivery. The Deep Space Network (DSN) was created to directly address this bottle neck for missions traveling beyond Earth and has since enabled every deep-space NASA mission. Close to Earth, the Near Earth Network (NEN) provides a similar service. Memory storage capabilities have also advanced significantly. The advent of tape drives gave substantial storage capacity to spacecraft. However improvements in RAM and flash technologies have allowed these to greatly surpass all other storage methods with fewer moving parts.

Seventeen different missions are considered and include a mixture of deep-space, Mars, and near-Earth spacecraft. The total raw data production downlinked to Earth is given along with the average yearly data production rate. Further, these missions' telecommunications rates and memory systems are briefly discussed and compared. While this data exists in a variety of forms and documents, it has not been collected and presented in this manner before.

This paper outlines the improvements in spacecraft capabilities over time, focusing on key events or improvements. Technology changes are not the direct focus so much as what has caused the use of technology as it develops. The ground infrastructure of the NEN and DSN is also discussed covering similar key events that are related to the spacecraft events. The planned NASA-Indian Space Research Organization (ISRO) Synthetic Aperture Radar (NISAR) mission is discussed and shown to be expanding the current-day limitations of both ground and spacecraft technology. Finally, the accumulated capabilities are shown for the explored missions and discussed.

2. History of Several Key Missions

Several missions and their methods for handling data are described briefly. While focus is placed on deep-space missions, many of the lessons learned are applicable to near-Earth missions.

The Voyager Mission

The Voyager mission was originally created to explore Jupiter and Saturn using a suite of sensors to measure the magnetic fields, composition of particles in the surrounding space, energy emissions from a variety of sources (comic rays, the sun, planets), and image the planets.[13] The mission was extended to fly-by Neptune and Uranus and extended again for the current Voyager Interstellar Mission.

At the start of the Voyager Mission the methods by which data were created and sent to Earth were still fairly new. While the Pioneer 10 and 11 spacecraft had made it to the outer planets, the process of retrieving data from deep space presented many unknowns. Due to the nature of the mission producing data in bursts as the spacecraft flew by the planets of interest, not only was a data recorder needed, but any information created was highly valuable and could not be recovered at some later time because the spacecraft was beyond the planet. When transmitting data back to Earth, data handling was very conservative.

At first, Voyager utilized a convolutional and Golay coding having a symbol rate equal to twice the bit rate.[3] For the phase of the mission up to Saturn, this meant that one error correction bit was transmitted for every information bit. In an effort to reduce the large overhead of the Golay coding, the Voyager spacecraft utilized the new Reed-Solomon (RS) encoding that only took one error correction bit for about every five information bits transmitted. The bit error rate was also dropped from $5x10^{-3}$ to 10^{-6}.[3] Imaging data were particularly challenging to handle simply due to the large amount of information created. Voyager used some simple, but effective, compression routines that greatly compressed the dark space regions of images while maintaining the target's higher resolution information.[3] Finally, Voyager was an early adopter of X-band radio systems, which have been used consistently since the Voyager mission, as shown in Table 4. In these ways, the Voyager spacecraft were able to demonstrate improved techniques for the transmission of data for space missions.

The Voyager spacecraft are a bit unique for the list of spacecraft considered as they are on a trajectory leaving the solar system, without a specific destination. Therefore, their capabilities are more time varying. For example, the current communications data rate is 160 bps[13] on the 34 m DSN antennas but a data rate of 7.2 kbps[3] was achievable in the mid-90's when the spacecraft were in the early Interstellar phases of the mission. During the planetary mission the X-band system could achieve up to 115.2 kbps (Table 4). Similarly, Voyager uses tape for data storage, making its capabilities variable given the input data rate of instruments used (ranging from tens to several hundred bits-per-second[3]).

The Galileo Mission

Galileo was a mission to Jupiter launched in 1989 and completed in 2003 when the spacecraft was purposely plunged into the Jovian atmosphere. During the mission the spacecraft studied the atmosphere of Jupiter using a probe, performed fly-bys of the moons while taking images, performing radio science, and measuring magnetic fields and particles.[1] While Galileo revealed much about Jupiter and its moons (including direct measurements of the planet's atmosphere and evidence of oceans on several of the moons that still tantalizes NASA), the unexpected product of Galileo was the many improvements in data processing caused by a failure.

In 1991, the Galileo spacecraft failed to deploy its High Gain Antenna (HGA)[1] while in its cruise phase to Jupiter. This could have led to the failure of the mission. Originally, the telecommunications data rate was expected to be at 134.4 kbps with the X-band HGA (Table 4). However, the HGA did not deploy correctly making that system unusable. The S-band Telemetry and Tele-commanding (TTC) link was only a 10 bps system, and therefore the science data return were also reduced to this rate.

Multiple improvements in data processing and telecommunication usage were implemented to allow the S-band system to return the science data. For data processing, a mixture of compression methods were developed. The Galileo team utilized both low-complexity lossless and lossy data compression and image editing schemes. This reduced the on board data volume without compromising the science objectives. The engineers and scientists tested the compression schemes on the best images available of Jupiter to see the effect of compression. Based upon these tests, it was demonstrated a priori to the science team that the methods were adequate. Because the majority of data were imagery, compression algorithms were optimized for images via integer cosine transform.[1]

For the telecommunication system, various changes were made to the encoding of data to improve bandwidth while minimizing errors in the data stream. To improve signal-to-noise ratio (SNR), an advanced convolutional and RS encoding was used. The originally planned RS format was less robust to burst errors caused by the updated compression schemes. This caused a shift to more robust RS coding and four levels of redundancy in the code. When decoding, the data were passed through a loop of successive levels of RS and Viterbi decoding.[25] Further, this type of encoding was prone to bursty error propagation therefore each image was broken up into sets of 8 lines of pixels, reducing the effect of this issue.[1]

The mixture of these improvements to the data packaging helped improve the overall data rate of Galileo by a factor of 10 (from about 10 bps to 100 bps). With the DSN improvements (mentioned later), this increased the data rate by another factor of 10. Galileo's S-band data rate was transformed from 10 bps to 1000 bps and because of these efforts, the Galileo mission achieved 70% of original objectives even with the greatly reduced downlink rate.[1] The planned and achieved capabilities of Galileo are shown in Table 4. Unfortunately, an aggregate data production for Galileo has not been tracked. However, the estimated data production through the prime mission is estimated to have been about 20 Gb.[2] In Table 3, the total data generation for the mission is estimated to be greater than 30 GB.

Cassini-Huygens Mission

Cassini-Huygens was a mission to Saturn and its moons that achieved orbit on July 1, 2004. After sending the Huygens probe to Titan, Cassini received two follow-on missions (Equinox from 2008-2010 and Solstice from 2010-2017) and will perform a final plunge into Saturn's atmosphere in 2017.

The Cassini mission's objectives have been to study the planet of Saturn including its atmosphere and magnetosphere through multiple seasons on the planet. Cassini has also studied the ring features and composition as well as the complex moons of Saturn. The Huygens probe studied the Titan atmosphere and imaged the surface as it descended.[5]

Cassini has and continues to utilize previous mission's advances. For example, Cassini used the Deep Space Transponder, also used on Pathfinder, as its radio. This system was capable of a wide range of data rates (5 bps up to 248,850 bps on ground and in early cruise phase while doing Earth and Venus fly-bys).[4] Also based upon the advances of the Voyager and Galileo spacecraft, Cassini utilized an efficient RS coding and data compression. This has allowed data rates up to 166 kbps from Saturn.[4]

More Recent Deep Space Missions

More recently, in the 2000's and 2010's the focus has shifted from learning about the best methods for sending data to Earth, to improvements in the technologies and/or methods for data collection that support science needs. Generally instrument data production, downlink rates, and storage capacity show growing trends. Table 4 shows these changes for each mission. It is important to observe that while improvements in all of these capabilities do occur over time, comparing similar missions to each other is necessary. The various Mars orbiters (Odyssey, MRO) increase in capability as time progresses, similar to the rovers (MER vs. MSL) or the Jupiter missions (Galileo vs. Juno). This has been caused by a number of factors, given below.

Mars Exploration Rovers (MER)—MER generally communicate through relay satellites around Mars (Odyssey and the now decommissioned Mars Global Surveyor or MGS) but could directly send transmissions to Earth; communications with the 34 m DSN stations through the rover's low gain antenna was possible but cut the data rate to about 10 bps. MER's X-band system came from the Deep Space 1 mission, launched in 1998, that helped demonstrate a number of technologies. One of the most important was the Small Deep Space Transponder (SDST)[19] an X-band system purpose-built for JPL's missions and a slimmer version of the Deep Space Transponder from Cassini and Pathfinder.

Relay satellites are used extensively for MER and communicate through a UHF system. Originally, it was planned that about 60% of the data would come through this link and transmit at up to 128 kbps. During the extended missions, the 256 kbps capability was used more often. By the end of the prime mission, UHF had actually returned 89% of the mission science data. UHF has been used increasingly and by the end of the first extended mission, 97% of the data were returned through the UHF relay system.

Other improvements to the rovers' capabilities to transfer more data came from several operational improvements. It was quickly found that orientation of the rovers made a notable difference in data return capability (due to gimbal slew range and gain pattern). Planning the rover's orientations during passes was done to help increase through-put. Further, MER was the first deep space JPL project to use communication windows, the idea of preplanned communication with all parameters defined, including start and end times. This gave greater flexibility to the planning of the mission and allowed for better optimization of the windows.[6]

Mars Reconnaissance Orbiter (MRO)—The MRO mission was built to map Mars in high resolution. This remote sensing platform has been able to characterize the atmosphere, surface, and subsurface of Mars. One of the goals was for MRO to identify landing areas for future missions which it was able to do for MSL and Phoenix. Finally, MRO was designed to be a relay for Mars landers and rovers, not only for nominal surface data but also during the critical atmospheric entry, decent, and landing phase.

MRO represents an important piece of infrastructure for Mars missions because of this relay capability. Unlike many deep space missions, Mars missions have a relatively large amount of capability due to the number of assets available for use. Like Odyssey or MGS, MRO continues to effectively increase bandwidth for surface missions. Because it is so costly, in terms of mass, to land something on a planet, reducing size and complexity for those landing systems is important to maximize the instrument payload and landing system's science-based capabilities. Having a relay spacecraft in orbit allows surface vehicles to have much higher data rates with the relay (i.e. the shorter distance to Mars orbit versus Earth reduces power required). The relay spacecraft in turn have more capability to send information to Earth, simply because the systems are not as constrained and can support more capable communication systems.

Due to the aforementioned science and relay requirements for MRO, its capabilities are quite impressive, as shown in Table 4. MRO primarily uses an X-band transmitter to send data to the DSN but also has a UHF capability to communicate with landed assets.[8] MRO does not perform as a relay for the MER rovers. (MER-Spirit, prior to decommissioning, actually used the same DSN channel as MRO to communicate direct to Earth causing the two vehicles to coordinate downlink schedules to avoid interference.[6,8]) However, MRO acted as a relay for the Phoenix lander and continues to relay data for the MSL rover.[8]

The MRO mission is unique in having a detailed day-by-day tracking system for the amount of data produced and the total data downlinked. By the end of MRO's prime mission in September 2010, it had created 50 Tb of data. By the start of the third extended mission in September 2014, MRO had produced 160 Tb. As of August 22, 2016 the MRO mission had produced 207.5 Tb of data, as shown in Table 3.

Mars Science Laboratory (MSL)—MSL's primary mission is to better characterize Mars' past capability to support life. It does this through providing the capability to conduct numerous in-situ measurements of the rover's environment (atmospheric, rock and dirt samples, etc.). The rover is highly capable and has been described as having a mobile laboratory on the surface of Mars.

In terms of data handling, MSL is a logical evolution from MER. Similar to the MER rovers, MSL uses an X-band command and telemetry system as well as a UHF system. The X-band can perform direct to Earth transmissions but at relatively slow rates for telemetry transmission. The X-band system uses an updated SDST where a coherent leakage issue was removed, a consistent problem on MER. MSL has a higher effective information rate due to the radio's capability to have an increased bit rate and good coding efficiency. MSL has improved data return by about 70% from MER on the X-band system at low rates. The successful MER demonstration of UHF data relay to MGS and Odyssey created the concept of operations for MRO becoming the workhorse for any future landed assets.[9] This allowed the MSL UHF system to communicate with MRO at rates up to 2 Mbps, and to Odyssey at rates up to 256 kbps (like MER).

Juno—The Juno mission's objective is to measure Jupiter's atmosphere (water abundance, composition over a variety of depths) and map the magnetic and gravitational fields.[10] Juno is still in its early prime mission science campaign, but has started to return data. It is expected that during the prime mission, Juno will return near 1.5 Tb of science data.

All missions must handle bursty data. As stated before, missions like Voyager had short periods of activity, but they were followed by large time gaps between targets, allowing for recorded data to be sent to Earth. An orbiting mission like Juno has similar large periods of data production near a fly-by but also has a shorter time frame to send this data to Earth, compared to Voyager, prior to the next pass around Jupiter. Juno plans to take data in a consistent manner each orbit to get similar measurements over different areas of Jupiter as the spacecraft longitude drifts.[10] This means that there is a fundamental data set that Juno always needs to collect and transmit to Earth. This causes a challenge as downlink capacity (data rate) depends upon the relative distance between Earth and Juno.

As explained by Stephens,[10] Juno has selected two primary data collection methods. The first is downlink constrained, when the distance is large, and the net return per day is smaller. This drives data collection to focus on the fundamental data set and the mission does not use margin in the plan (retransmission can cause data loss). The second, when the distance is smaller, there is more bandwidth than data storage capacity on-board. Data collection is more flexible in this case as the larger transmission bandwidth can be filled, only being restricted by on-board storage capacity. Both retransmission and additional data collection are possible.

Europa Mission (Planned)

The upcoming Europa Mission planned to launch in 2022 would study Jupiter's moon and determine many characteristics of Europa's suspected liquid water sub-surface ocean. The mission is focused on characterizing how much liquid water is present, its salinity, the thickness of Europa's ice shell along with other properties. NASA has selected nine instruments including cameras, radar, a spectrometer, magnetometer, thermal imager, dust analyzer, spectrograph, and plasma magnetic sounding.

Similar to Juno, the Europa Mission is planning long duration orbits about Jupiter. The Europa Mission would frequently have flybys of the moon separated by approximately 2 weeks. During orbital plane change maneuvering, these flybys can be separated by longer durations, around 100 days. Flybys would only last a few hours; the average estimated time being 16 hours. Because of this, only a limited amount of data would be produced by the spacecraft, around 60 - 70 Gb for each pass. Given a planned prime mission of about 45 flybys this yields the estimated 2.6 Tb of data (Table 3).

The Europa Mission is designed to fit within the capabilities currently existing for the DSN, memory capacity, and telecommunications. The harsh radiation environment is a partial driver for staying within well established, rad-hard technology boundaries. Currently, the mission is planning to maintain fairly large margins on data production and storage to ensure data is properly received on the ground. For example, the observable data throughput between the spacecraft and Earth, using the Ka-band system, is estimated to be 5.6 Tb. Given memory constraints, including storage time of less than 8 weeks due to radiation degradation, this is reduced to 4.9 Tb. The planned data collection is 2.6 Tb or yielding a margin of about 47%. Of course, more detailed planning is done at the flyby level and as the mission gets closer to launch, total data generation may increase. Further, there are significant lengths of time (between flybys of Europa or during maneuvering) when other opportunistic measurements can be made of other icy bodies about Jupiter.

Earth (and Near-Earth) Orbiters

Many of the missions for Earth observing satellites involve large data production. Imaging, high-resolutions, and global coverage are often requirements. While the Lunar Reconnaissance Orbiter (LRO) does not orbit Earth, it also was an imaging mission. Only more recent Earth missions are examined in Tables 3 and 4 but the great difference between the deep-space and near-Earth vehicles' capabilities can be seen. This difference exists because Earth orbiting vehicles have a number of advantages, given the parameters studied here, not available to deep-space missions.

Near-Earth spacecraft are closer, allowing for increased communication rates. For example an X-band radio system in LEO could have a space loss term of about 178 dB while a vehicle at Mars could have an average loss of 280 dB. Near-Earth spacecraft also have the advantage of greater availability for ground communications (through the NEN or other sites), and therefore have much more ability to send data to the ground. This also eases some of the storage constraints because data can flow much more quickly through the system, allowing for even more data collection. Due to shared DSN resources and geometry of the deep-space missions, they are often not allowed such consistent contact. While DSN track times are often much longer than any single NEN pass, the less consistent contact drives how and when data is taken and more time is required at the slower data rates.

Near-Earth spacecraft use this to their advantage. For example, EOS-Aqua routinely downlinks each orbit.[28] Aqua, operated by Goddard Space Flight Center, studies water in all its forms on Earth and needs continual downlinks to send data from its multiple instruments as it produces, on average, 89 GB of data a day.

More recently, the United States Geological Survey's (USGS) Landsat-8 has been demonstrating the large through-put required of this (and the next) generation's spacecraft. As shown in Table 3, LandSat along with the planned Surface Water Ocean Topography (SWOT) and NISAR missions will produce thousands of terabits per year. NISAR and SWOT are planned to take consistent, relatively unvarying data sets. Conversely, Landsat-8 behaves closer to an opportunistic and operational asset. These big data sets not only drive the large telecommunication and memory capabilities on these missions, but also the ground systems that need to handle these different types of missions.

3. Ground Network Evolution

Deep Space Network

The DSN has been in operation since 1958. To provide global sky coverage, it has ground stations that are approximately 120 degrees apart in longitude with permanent stations at

Table 1. DSN Capabilities,[19–21] excluding the 26 m antennas at each site

Site	Name	Size (m)	Tx. Freq. Band	Rx. Freq. Band
Goldstone, USA	DSS 14	70	S and X	S and X
	DSS 15	34 (HEF)	S and X	S and X
	DSS 24	34 (BWG)	S, X, and Ka	S, X, and Ka
	DSS 25-26	34 (BWG)	X and Ka	X and Ka
Madrid, Spain	DSS 63	70	S and X	S and X
	DSS 65	34 (HEF)	S and X	S and X
	DSS 54	34 (BWG)	S, X, and Ka	S, X, and Ka
	DSS 55	34 (BWG)	X and Ka	X and Ka
Canberra, Australia	DSS 43	70	S and X	S and X
	DSS 45	34 (HEF)	S and X	S and X
	DSS 34 - 36	34 (BWG)	S, X, and Ka	S, X, and Ka

Goldstone, U.S.A, Canberra, Australia, and Madrid, Spain since the 1960's. Each site has a 70 m antenna and between two to five 34 m antennas.[19] Note that the DSN also has 26 m antennas to communicate with Earth orbiting spacecraft, but those are not discussed here. The stations are capable of receiving and transmitting in the S, X, and Ka-bands (Table 1).

Throughout its history the DSN has continued to evolve, often making advances in support of flight projects as they become more sophisticated. During the early deep space missions, engineers were learning how transmit data with high reliability. As experience was gained, it appears that this became less of a focus. The more recent changes focus on improvements and increases in efficiency to RF systems, including more automation. Highlights from several missions are detailed here.

During the Voyager mission, the DSN underwent major updates and improvements, most notably the increase in antenna size from a 64 m dish to the 70 m dish. Further, during the Neptune and Uranus encounters, the DSN was shown to be able to operate as an array with other (relatively) near-by sites that were able to effectively double the data rate of the telecommunications.[3] On Galileo, the 70 m and 34 m antennas were arrayed often (of up to six antenna from across the world). Due to Galileo's antenna deployment failure, further amplifier and receiver improvements were made to increase gain of the system and improve downlink bit rates through the low-gain antenna. These items helped to improve the bit rate by a factor of 10.[1] Cassini also often used arrayed 34 m and 70 m stations. During 2001, while in cruise to Saturn, all 70 m antennas were equipped with X-band uplink capabilities for the first time. These upgrades were driven by Cassini's need to use its LGA at Saturn.[4]

The DSN has two types of 34 m antenna: High Efficiency (HEF) and beam waveguide (BWG). Prior to MER the BWG were lower performance, but they had transmitter power increases to 20 kW and the antenna feeds were updated. This made the performance of the HEF and BWG nearly the same. Since the rovers are capable of direct DSN communication through X-band and relay communication through Mars orbiters, the DSN is able to communicate to the rovers and orbiters at the same time allowing for simultaneous downlink of data.[6] Currently, the system is capable of transmitting and receiving from all of its antennas and can use S, X, and Ka-band systems. The DSN also continues to provide useful science and navigation (Doppler and ranging) information for all missions.[19] For example, on the Juno mission the DSN is used for both X-band and Ka-band gravity science as well as downlink of telemetry and ranging through the X-band system.[10] Generally, the 70 m antennas are used for Juno.

Looking ahead, the DSN is expected to have about 100 Mbps connections between the three sites (Goldstone/Madrid/Canberra), in early 2017. This is being done mainly to accommodate higher rate data return with reasonable latency. The DSN will be supporting multiple missions with data rates in the hundreds of megabits per second over the coming decade. The DSN is anticipating that by 2017 TESS will be using 125 Mbps, and NEOCam would use 150 Mbps around 2020. Finally, the potential use of the DSN by WFIRST would increase DSN capabilities to about 300 Mbps by 2024.

NASA Near Earth Network (NEN)

The NEN, Table 2, has been in operation since 1958 under various names. Starting with the need to maintain contact with human spaceflight missions, evolving and expanding with changing satellite demands, and finally incorporating commercial entities, the NEN provides significant coverage and bandwidth capabilities for NASA.[16] The NEN, like the DSN, also can provide navigation (Doppler and ranging) information from many of its antenna.[18]

Starting in the 1990's the NEN added multiple polar stations, such as Alaska Satellite Facility[17] to support the large data production (and downlink needs) of the spacecraft at that time.[16] These stations have been extensively used by low Earth orbit science missions. However, the NEN has the capability to support missions beyond low Earth orbit. Many other upgrades to the NEN throughout the years have been to improve performance as well as increase automation. For example, the 18 m station at White Sands, NM was upgraded to have Ka-band capability for the LRO mission.[15] Upcoming Ka-band systems are shown in Table 2 denoted by [**Ka**]. The NEN currently consists of 15 sites each with multiple antennas, the largest of which is 18 m, and the system is capable of VHF, S, X, and Ka-band frequencies.[15,18]

The NEN is now considering adding another high latitude,

Table 2. NEN Capabilities[18]

Site	# of antenna	Size (m)	Tx. Freq. Band	Rx. Freq. Band
Fairbanks, Alaska	2 operational	10 - 11.3	S	S and X
North Pole, Alaska	5	5 - 13	L and S	S and X [**Ka**]
Florida	2	6.1	S	S
Hartebeesthoek, South Africa	2	10, 12	S	S and X
South Point Hawaii	2	13	S and X	S and X
Dongara, Australia	2	7.3, 13	S and X	S and X
Kiruna, Sweeden	2	13	S	S, and X
McMurdo, Antarctica	1	10	S	S, and X
TrollSat, Antarctica	1	7.3	S	S, and X [**Ka**]
Svalbard, Norway	3	11.3 - 13	S	S, and X [**Ka**]
Santiago, Chile	3	9 - 13	S	S
Singapore	1	9.4	S	S and X
Wallops Island, Virginia	4	Quad Yagi, 4.7, 11.3	VHF and S	VHF, S, and X
Weilheim, Germany	2	15	S	S
White Sands, New Mexico	3	Quad Yagi, 18.3	VHF and S	VHF, S, and K/Ka[15]

southern ground station at the tip of Chile. Further, multiple high latitude stations, due in large part to the upcoming generation of spacecraft with unprecedented data generation (NISAR, SWOT), are being upgraded[15,17] to utilize Ka-band telecommunication systems. The NEN is also upgrading to multi-gigabit per second data rate capabilities for these stations.

4. NASA-ISRO SYNTHETIC APERTURE RADAR (NISAR)

NISAR is a planned Earth Science Radar mission, being jointly developed by JPL/NASA and the Indian Space Research Organization. The NISAR science payload will feature a dual frequency (L and S-band) Interferometric Synthetic Aperture Radar. JPL/NASA will provide the L-SAR electronics, along with the 12-meter deployable reflector and radar instrument structure, which also hosts the ISRO-provided S-band payload electronics. ISRO is providing the spacecraft bus and the launch vehicle as well. NISAR is specifically discussed because of the large data volumes it will produce and the fact that it necessitates capability improvements.

The science disciplines that will benefit from NISAR data include:

1) Ice dynamics: ice sheets, glaciers, and sea level
2) Ecosystems and biomass changes
3) Solid Earth deformation including hazard response i.e. volcanoes or earthquakes
4) Coastal processes in India

The mission is designed to provide near-global coverage, using the L-band radar, of all the land surfaces of the Earth every 12 days. For the selected mission orbit (747 km), this requires a radar with a swath capability of 240km at the equator.

The polarimetric capabilities of the radar vary from transmitting in one polarization and receiving in the same polarization up to transmitting using two polarizations and receiving in two polarizations simultaneously. Taken together with the large swath capability, this results in significant quantities of data collected. Furthermore, with the multi-disciplinary aspect to the mission, numerous targets are observed each orbit, resulting in a daily production and downlink requirement of nearly 26 Terabits per day for NISAR. At the conclusion of the planned three year primary science phase, it is expected that NISAR will be able to detect changes up to 1 cm for most applications.

New Capabilities for NISAR

NISAR is pushing the boundaries of current capabilities and requires improvements in several key areas to meet science objectives. First is the telecommunications system that will require multi-gigabit per second data rates in order to transport all of the collected data. NISAR's architecture is to transmit data direct to Earth (DTE) and will therefore use the NEN and its partner stations, primarily KSAT. Given that the spacecraft will orbit Earth 14.4 times per day, on average NISAR needs 1.8 Tb of downlink capacity per orbit to get all 26 Tb to the ground. This means NISAR requires consistent access via the use of polar ground stations. NISAR will use a 3.45 Gbps downlink data rate allowing the data to be downlinked in about 7.5 minutes. However, due to orbit geometry, not all orbits allow for polar station contact. Further, the data are created inconsistently (Figure 1) as some orbits have mostly ocean without data collection while others may stretch across multiple continents. This drives the need to have, on average more than one pass per orbit. In a day, NISAR intends to use about 17 passes. When looking at average pass times, this equates to a capability of about 30 Tb in a day.

On the flight side, JPL has invested in the development of a new Ka-band modulator for science data transmission. The Universal Space Transponder (UST) is intended to be the next generation Ka-band radio for near-Earth and deep space missions for JPL. The UST is effectively the follow-on for the X-band SDST. NISAR will be the first mission to use this radio. This system is moving away from the RS encoding scheme and moving to the higher efficiency Low Density Parity Check (LDPC) encoding. ISRO is also flying a separate high-rate Ka-band telecommunication system that communicates at 2.44 Gbps through the multiplexing of numerous lower data rate modulators to downlink data over ISRO stations.

On the ground side, as mentioned in the previous discussion on the NEN and by McCarthy et. al,[15] the NEN is currently improving their systems to handle these large rates. Table 2 shows the planned Ka-band upgrades to the existing infrastructure (indicated [**Ka**]). The ISRO stations (ISTRAC) are also being upgraded to Ka-band. Further, for added mission robustness, both JPL and ISRO Ka-band systems are capable of communicating with both the NEN and ISTRAC stations. Therefore, NASA and ISRO ground networks need to be relatively quickly configurable to work with the other systems' format (CCSDS is used across both Ka-band systems). NISAR is also generally using dedicated data lines from the ground stations to deliver the data quickly to the Ground Data Systems (GDS). This has limited the use of stations like TrollSat because it is expensive for both time and cost. TrollSat transmits received data through another relay satellite which does not lend itself to NISAR's mission profile (delaying application-based use and increased cost) or TrollSat's capabilities (data volume). These challenges push the ground networks to have a variety of capabilities.

One other area that NISAR is pushing current capabilities is on-board memory storage. As shown in Table 4, early missions utilized tape to record data. Starting in 1992, missions began to switch over to solid state recorders[23] (SSR), utilizing technology such as dynamic random-access memory (DRAM) because it had finally become dense enough, reliable enough, and had reasonable radiation tolerance characteristics to fly on space missions. The removal of mechanical systems also is a benefit as tape must be played and rewound. Tape winding failure was seen on Galileo[1] and caused a relatively large scare and replanning of the Jupiter Orbit Insertion event. By the late 1990's synchronous DRAM (SDRAM) became the norm for space missions.[23] Only recently has flash memory started seeing use. While more susceptible to radiation, many products are beginning to use flash as it is higher memory density than SDRAM. Flash also provides significant power savings.

The NISAR mission is utilizing flash due primarily to its high storage density, the large number of read-write cycles (over 100,000), and moderate power draw. (In early NISAR studies looking at SDRAM technology, the recorders were expected to take about 250 W; however, the actual NISAR flash SSR will take less than 150 W.) The use of flash was pioneered by EADS-Astrium,[23] now part of Airbus Defense and Space, and NISAR is utilizing their next generation recorder. The NISAR SSR provides 12 Tb (BOL) capacity and over a 12 Gbps combined I/O rate. This appears to be the first SSR ever built with the combination of such a large capacity and data rates. Note that while this SSR is incredibly capable, NISAR will still completely fill and drain the SSR over two times per day (Figure 1). This means that data will generally be on the SSR for about 11 hours before being transmitted and then automatically deleted, in preparation for new data. This is the driving reason why retransmission of data are not generally available for the NISAR mission.

NISAR is therefore enabled by gigabit per second telecommunications, on-board multi-terabit memory, multi-gigabit per second internal data rates, and improvements to ground networks to handle these data rates. However, once on the ground, data also need new handling methods.

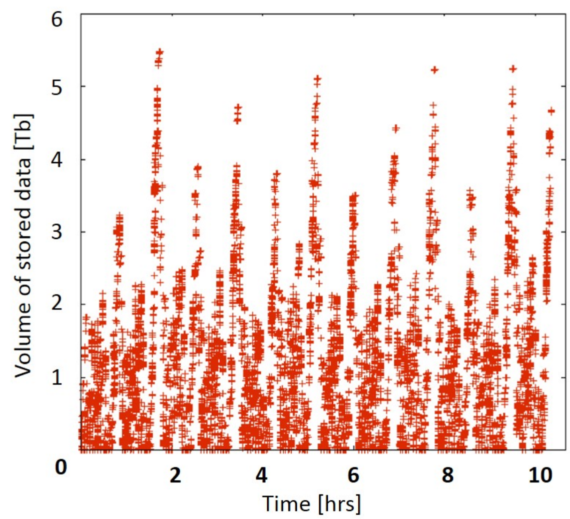


Figure 1. **Example of NISAR data collection over about 11 hours. Peak in this scenario is 5.5 Tb, average is 1.4 Tb**

NISAR Ground Data Handling

Memory is relatively inexpensive today when compared to the past. Many previous and current missions use onsite or other NASA based data storage servers. However, handling vast quantities of data are causing previously unencountered challenges, not only with respect to storage but also transferring those data to the users. As stated before, NISAR generates 26 Tb per day (3.25 TB) of raw data. After initial processing of the data into expected data products, that number balloons to 95 TB per day. (SWOT has similar issues, creating about 15.5 TB per day of processed data products.) This means that NISAR's ground data storage capacity is over 100 petabytes (PB) for the three year mission.

In order to handle this many data, the NISAR mission is adopting the use of commercially available storage systems. NISAR is purchasing space to be used for the project as data are produced and using cloud-based storage and access methods to distribute data thus enabling processing by the users. This also allows resources to be allocated based upon user demand so that overall data latency remains consistent independent of number of users. Still, the system must be capable of transferring data at many 10's of gigabits per second. The amount of information NISAR, and its users, produce is manageable by today's commercial storage industry which should be even more capable by the time of NISAR's 2021 launch. However, the volumes are large enough that they provide reasonable challenges.

5. Data Production

Table 3 gives the total raw, non-relay, data production for a selected set of past, current, and future missions. Note that this table is broken into two categories. The upper missions are deep-space and the lower section shows Earth orbiting (or near-Earth) missions. Table 4 gives some details of the telecommunications and memory capabilities of the same missions from Table 3. Note that data rate and information

Table 3. **Raw data production for variety of missions**

Launch	Mission	Data (Tb)	Date of Data	Yrs of Operation	Avg. Data (Tb/yr)
Sept/Aug. 1977	Voyager 1 & 2	5[12]	April 2014	36.58	0.14
Oct. 1989	Galileo	Est. 0.24	Sept 2003	13.91	0.019
Oct. 1997	Cassini	7.86	June 2016	18.67	0.46
April 2001	Mars Odyssey	135.34	June 2016	15.17	9.81
June 2003	MER-Spirit	23.17	May 2011	7.91	3.22
July 2003	MER-Opportunity	63.97	June 2016	12.92	5.44
Aug. 2005	MRO	207.5	August 2016	11.06	18.77
Sept. 2007	Dawn	1.65	Oct 2016	9.09	0.20
Aug. 2011	Juno	1.5	Feb. 2018	Est. 6.50	0.25
Nov. 2011	MSL	101.62	June 2016	4.58	24.38
Est. 2022	Europa Mission	2.6	**Planned**	Est. 3	0.84
May 2002	EOS-Aqua	$\approx$3745.05[28]	Oct 2016	14.41	259.88
June 2009	LRO	5610.67	June 2016	7	881.29
Feb. 2013	Landsat 8	20064[27]	May 2016	3.22	6853.17
Est. 2020	SWOT	8650.5[26]	**Planned**	Est. 3	2883.5
Est. 2021	NISAR	27922.5	**Planned**	Est. 3	9307.5

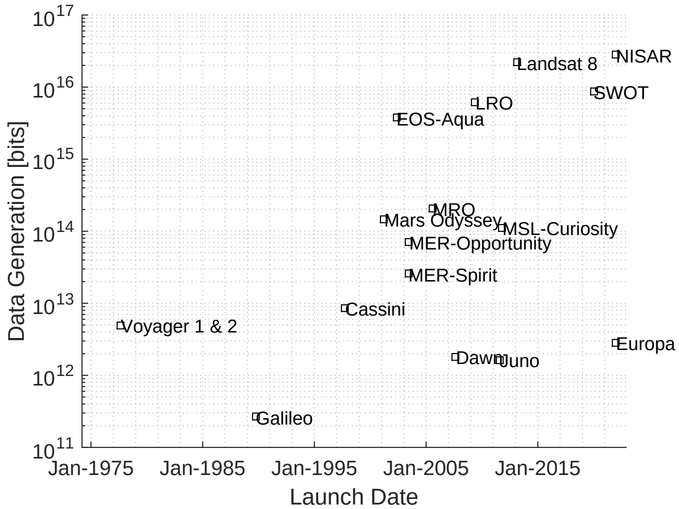
Table 4. **Technology capabilities of a variety of missions: Downlink telecommunication rate and memory capacity**

Mission	Max. Telecomm Rate (bps)	Freq. Band	Memory Capacity (b)	Memory Technology
Voyager 1 & 2	115.2k($<$'90), 160 ('16)[3,13]	S & X-band[3]	Variable	Magnetic tape[12]
Galileo (planned) Galileo (actual)	134.4 k[1] 1 k	X-band[1] S-band	Up to 912 M	Magnetic tape
Cassini	166 k[4]	X-band[4]	2 G	DRAM
Mars Odyssey	110.6 k[24]	UHF (relay) & X-band[24]	1.024 G[24]	DRAM[24]
Both MER	28.8 k (X) & 256 k (UHF)[6]	X-band or UHF[6]	1.792 G[7]	flash[7]
MRO	6.6 Msps	X-band	160 G (BoL), 100 G (EoL)	SDRAM
Dawn	124 k	X-band	24 G	DRAM
Juno	200 k[11]	X-band[10]	32 G (BoL), 29 G (EoL)[10,11]	SDRAM[11]
MSL	4 k (X) & 1.35 M (UHF)[9]	X-band or UHF[9]	32 G[9]	flash
Europa Mission	150 k & 1 M	X & Ka-band	512 G (EoL)	Under study
EOS-Aqua	150 M	X-band[28]	136 G[28]	SDRAM
LRO	300 M[22]	S & Ka-band[15,22]	400 G[22]	SDRAM[23]
Landsat 8	384 M	X-band	3.84 T (BoL), 3.14 T (EoL)	SDRAM
SWOT	620 M[26]	X-band[26]	4.2 T (EoL)	flash
NISAR	3.45 G	Ka-band	12 T (BoL)	flash

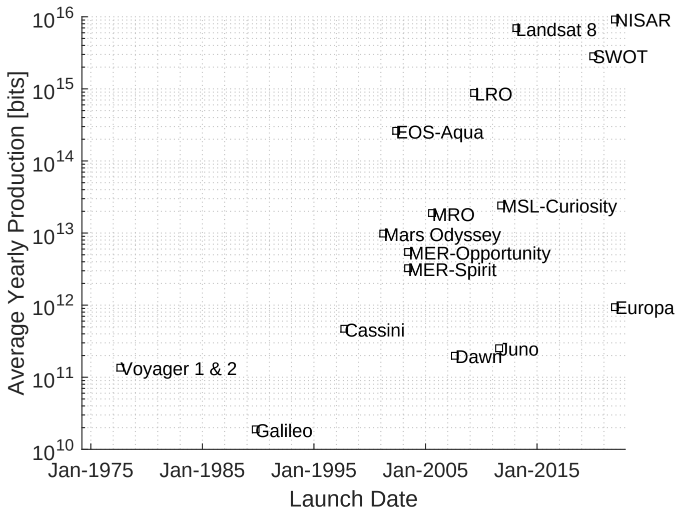
rate are used a bit interchangeably in Table 4 depending upon available data. This difference does not change the overall conclusions presented.

The impact of these missions and their discoveries have been tremendous. Still, especially for the deep-space missions, everything that these spacecraft have accomplished has been done in relatively small amounts of data. For example, both Voyager spacecraft have transmitted only about 5 Tb of data to the ground. While 5 Tb is a fairly large value, especially considering all the aforementioned limitations and challenges for these missions, it is still not as large as might be expected, given Voyager's impact. The Mars missions all generally have much higher capability, helped by the fact that Mars and Earth are relatively close and the space loss is smaller allowing for faster transmission rates. However, there is a relatively large infrastructure around Mars allowing the rovers and spacecraft to work cooperatively.

Conversely, Earth missions have comparably easy communication constraints. The very short transmission distances and availability of many ground assets allow for a much larger volume of data to be transmitted. This is shown by the large differences in the total and average amount of data production in Table 3.



(a)**Total data return for missions over history**



(b)**Average yearly data return for missions over history**

Figure 2. Data Production for NASA missions given Table 3. Note the log scale on the data axis.

Figure 2 shows both the total amount of data produced for all studied missions, and the average data production by year for each mission. It is clear from Figure 2 that there is a wide distribution of how many data are generated for each mission. Figure 2(a) shows that deep space missions have, or are expected to, return around several terabits of data and this trend remains somewhat flat. Mars missions all cluster together spanning tens to hundreds of terabits of data. Earth orbiters on the other hand, return petabits of data and appear to be on an upward trend.

When looking at average yearly production, Figure 2(b), similar trends are obvious. Deep space missions beyond Mars all seem to generate similar levels of data, below a terabit each year, even for the future Europa Mission. While the expected data return looks to be flat, the average yearly production is increasing, demonstrating that the more recent missions are expected to be of shorter duration. The Mars missions remain clustered together, around single to several tens of terabits per year but may also be trending upwards. Note that the amount of data relayed by MRO is not accounted for in the numbers represented in Table 3 and Figure 2. Finally, the near-Earth missions produce over 200 Tb per year or more and are continuing to increase in data return.

When looking at the data, there are a large spread in overall capabilities. However, the memory capacity generally seems to follow Moore's Law. Eq. 1 shows Moore's Law which, somewhat qualitatively, states that computing power doubles every 24 months. In Eq. 1 the time t is represented in months.

$$y_n = 2^{t/24} y_0, t : t_0 \to t_n \tag{1}$$

Figure 3 shows the deep space missions and their memory capacity. Using the future Europa Mission's capacity as a baseline (i.e. y_n at t_n), Moore's Law from Eq. 1 is also plotted on Figure 3. This line does a reasonable job of fitting the data with a $R^2 = 0.891$, but residuals are high demonstrating that Moore's Law is still only qualitatively accurate. Moore's Law also is a reasonable approximation for the near-Earth orbiters (when using NISAR's memory size or telecommunication rates as the baseline y_n at t_n to draw the line in Eq. 1) partially characterizing both memory growth ($R^2 = 0.847$) and telecommunications data rate growth ($R^2 = 0.824$). It makes sense that Moore's Law fits memory size since the law itself relates to transistor density and memory capacity is directly associated with this. However, when all missions are considered together all of the R^2 values are very low. This result further demonstrates that deep-space and near-Earth missions do not have the same capabilities (initial conditions) but roughly do follow their own independent Moore's Law growth. Telecommunication rates and net data production have many other factors, as described in part by this paper, beyond what Moore's Law applies to and therefore do not fit this model either.

6. SUMMARY

Given the status of past, current, and future missions it appears that several trends may continue. Because much of the "low hanging fruit" science objectives have been realized with past missions, the next class of discovery takes more detailed information and observations. Mission requirements continue to list high-resolution, global coverage, or long time-series data to meet the science objectives. Thus, flight and ground systems will be required to continually advance in capability. This is shown by the ever increasing data production trends for missions over time.

Even with increased need for detailed measurements, deep-space missions will likely continue to produce, and return to Earth, fewer overall data simply due to the vast distances involved and more limited resources. However, with incremental improvements in abilities to store data and transmit at higher rates (Ka-band), it is likely that many missions will receive a noticeable increase in capability. However, because the currently most interesting science targets are often in more harsh environments, the durations of future missions may be shorter keeping overall data return fairly flat. Earth orbiting missions are likely to persist in producing more and more data as both flight hardware and ground infrastructure improve. Mars missions will probably continue to have a healthy infrastructure to use as is demonstrated by the fact that old and relatively new orbiters (such as Maven) are also charged with providing data relay for ground assets. However the adaptation of Ka-band systems is probably a number of

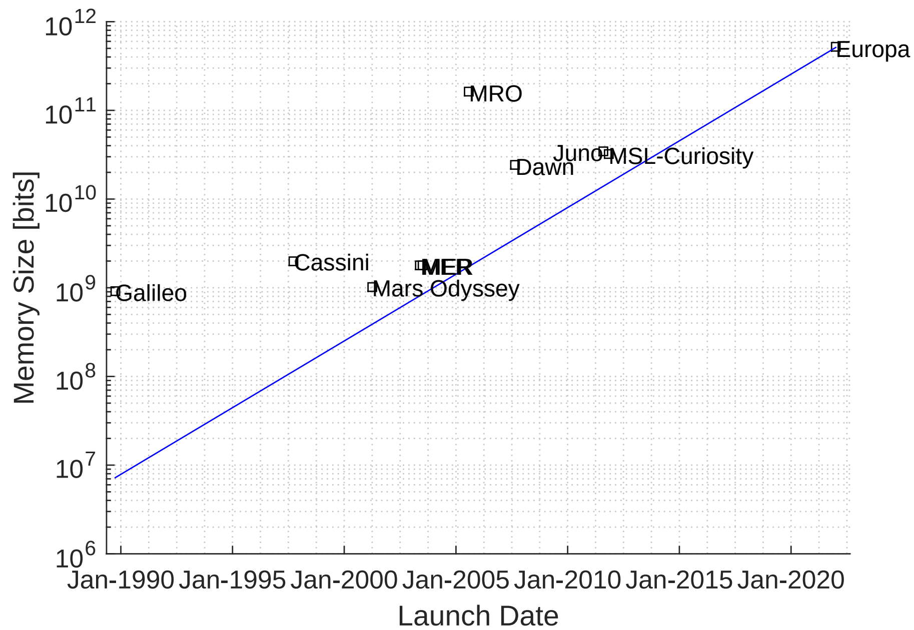


Figure 3. **Memory capacity of deep space missions. Moore's Law shown for comparison, using Europa Mission's capability as the maximum point**

years away. The quick rate of improvement in SSRs will greatly aid many missions. Flash technology still has some issues for deep-space applications due to its susceptibility to radiation, but it seems probable that flash SSRs' benefits (high density, low power) outweigh the issues.

ACKNOWLEDGMENTS

The authors would like to thank several people, mostly from JPL, who provided information for this paper. Jordan Padams and Karen Boggs provided a number of the total data generated values for the discussed missions. Dave Bell and James Erickson helped provide information and facts concerning the Galileo mission. Jason Kastner and Bobak Ferdowsi provided information about the in-development Europa Mission. Daniel Limonadi provided information about the in-development SWOT mission. Maher Hanna provided information about the NISAR Ground Data System. Stuart Stephens provided information about the expected Juno mission return. Travis Chezick (Goddard) provided information on Landsat 8. Chi Wu (Goddard) provided information about EOS-Aqua. Julie Webster provided information on Cassini's memory devices and downlink rates. Tim Pham provided several inputs on the future outlook for the DSN's improvements. Finally, Dr. Marc Rayman and Tim Weise provided information about the expected Dawn mission parameters and data return.

The work described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

[1] Taylor, Jim, Kar-Ming Cheung, and Dongae Seo. Galileo Telecommunications. Article 5. Pasadena: NASA-JPL/CalTech, 2002. DESCANSO Design and Performance Summary Series.

[2] Statman, Joseph I., Deutsch, Leslie J. Galileo's Telecom Using The Low-Gain Spacecraft Antenna. Pasadena: NASA-JPL/CalTech, 1996.

[3] Ludwig, Roger, and Taylor, Jim. Voyager Telecommunications. Article 4. Pasadena: NASA-JPL/CalTech, 2002. DESCANSO Design and Performance Summary Series.

[4] Taylor, Jim, Sakamoto, Laura, and Wong, Chao-Jen. Cassini Orbiter/Huygens Probe Telecommunications. Article 3. Pasadena: NASA-JPL/CalTech, 2002. DESCANSO Design and Performance Summary Series.

[5] "Cassini Mission to Saturn" NASA. NASA, 2016. Web. 9 Oct. 2016. https://saturn.jpl.nasa.gov/

[6] Taylor, Jim, Makovsky, Andre, Barbieri, Andrea, Tung, Ramona, Estabrook, Polly and Thomas, A. Gail. Mars Exploration Rover Telecommunications. Article 10. Pasadena: NASA-JPL/CalTech, 2005. DESCANSO Design and Performance Summary Series.

[7] Sosland, Rebekah, et al. "Getting back on the road: Reformatting flash memory on-board the Mars Exploration Rover Opportunity." 2015 IEEE Aerospace Conference. IEEE, 2015.

[8] Taylor, Jim, Lee, Dennis K., Shambayati, Shervin. Mars Reconnaissance Orbiter Telecommunications. Article 12. Pasadena: NASA-JPL/CalTech, 2006. DESCANSO Design and Performance Summary Series.

[9] Makovsky, Andre, Ilott, Peter, Taylor, Jim. Mars Science Laboratory Telecommunications System Design. Article 14. Pasadena: NASA-JPL/CalTech, 2009. DESCANSO Design and Performance Summary Series.

[10] Stephens, Stuart K. The Juno Mission to Jupiter: Lessons from Cruise and Plans for Orbital Operations and Science Return. IEEE Aerospace Conference, Montana, Big Sky. IEEE, 2015.

[11] Stephens, Stuart K., Hirst, Edward A., Nybakken, Derrick J. Juno Project Mission Plan. Revision D. Pasadena: NASA-JPL/CalTech, 2013.

[12] "Did You Know?" NASA. NASA, 3 Mar. 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/mission/didyouknow.html

[13] "Interstellar Science." NASA. NASA, 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/science/index.html

[14] "Spacecraft Lifetime." NASA. NASA, 3 Mar. 2015. Web. 3 Sept. 2016. http://voyager.jpl.nasa.gov/spacecraft/spacecraftlife.html

[15] McCarthy, Kevin P., Stocklin, Frank J., Geldzahler, Barry J., Friedman, Daniel E., Celeste, Peter B. NASA's Evolution to Ka-Band Space Communications for Near-Earth Spacecraft. SpaceOps 2010, Huntsville, AL, April 25-30, 2010.

[16] "History" NASA. NASA, 22 Oct. 2015. Web. 3 Oct. 2016. http://esc.gsfc.nasa.gov/space-communications/NEN/gn-history.html

[17] Arko, Scott, La Belle-Hamer, Annette, McCarthy, Kevin, Thoman, Bruce, Tye, Rob. The Alaska Satellite Facility Ground Station. SpaceOps 2012, Stockholm, Sweden, June 11-15, 2012.

[18] Thoman, Bruce E. Near Earth Network (NEN) Users' Guide. Rev. 2, Greenbelt, MD: Goddard Space Flight Center, 2016.

[19] Taylor, Jim, ed. Deep Space Communications. Pasadena: JPL/Caltech, 2014. Deep Space Communications and Navigation Series.

[20] "Deep Space Network.", NASA. NASA, 2016. Web. 3 Dec. 2016. http://deepspace.jpl.nasa.gov/

[21] Jet Propulsion Laboratory. DSN Telecommunications Link Design Handbook. 810-005 ed. Vol. E. Pasadenda: Jet Propulsion Laboratory, California Institute of Technology, 30 Nov. 2000. Web. 3 Dec. 2016.

[22] "Building the LRO Spacecraft ." NASA. NASA, June 2016. Web. 8 Oct. 2016. https://lunar.gsfc.nasa.gov/spacecraft.html

[23] Ladbury, Ray. Updated Solid State Recorder (SSR) Radiation Guidelines. NEPP Electronic Technology Workshop, Greenbelt, MD, June 11-15, 2012.

[24] Makovsky, Andre. Mars 2001 Odyssey Telecommunications System Handbook. Revision 3.0. PD722-802. Pasadena: NASA-JPL/CalTech, 2001.

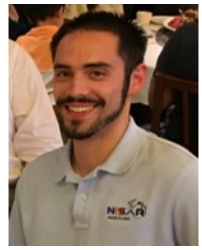
[25] Heller, J. A. and I. M. Jacobs, "Viterbi Decoding for Satellite and Space Communication," IEEE Transactions on Communication Technology, Vol. COM-19, October 1971, pp 835848.

[26] Telecom Team. "X-band Telecom Subsystem." SWOT Preliminary Design Review. Jet Propulsion Laboratory, Pasadena. 18 Nov. 2015.

[27] Sauer, Brian. "Landsat Operations Report," Landsat Science Team. U.S. Geological Survey, July 26 2016.

[28] King, Michael D. "Aqua." Rpt. in Earth Science Reference Handbook. Ed. Claire L. Parkinson and Alan Ward. Washington, D.C.: NASA, 2006. 73-93.

BIOGRAPHY



Lee Jasper *received his B.S. and M.S. degrees in Aerospace Engineering in 2010 and a Ph.D. in Aerospace Engineering in 2014, all from the University of Colorado Boulder. He is currently working as a flight systems engineer at the Jet Propulsion Laboratory. His primary focus centers on the NISAR mission and is the systems engineer for the mission's solid state recorder.*

Peter Xaypraseuth *received his B.S. degree in Aerospace Engineering in 2000 from the California Polytechnic Institute. Peter is the lead flight systems engineer for the NISAR program.*